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# THE DESIGN AND EVALUATION OF HAIL SUPPRESSION EXPERIMENTS

PAUL T. SCHICKEDANZ and STANLEY A. CHANGNON, JR.

Illinois State Water Survey, Urbana, Ill.

## ABSTRACT

A statistical methodology involving the analysis of three basic types of historical hail data on an areal approach is presented for the planning and evaluation of hail suppression experiments in Illinois. The methodology was used to generate nomograms relating the number of years required to detect significant results to 1) type I error, 2) type II error, and 3) power of the test for various statistical tests and experimental designs. These nomograms were constructed for various area sizes and geographical locations within the State.

Results indicate that, for an Illinois experiment, insurance crop-loss data are the optimum hail measurement if the study area has more than 60 percent insurance coverage. The optimum experimental design is the random-historical design in which all potential storms are seeded on a particular day, and 80 percent of the forecasted hail days are chosen at random to be "seeded days." The recommended statistical analysis is the sequential analytical approach. If, however, conditions for the sequential analytical approach are not fulfilled by the data sample, the nonsequential approach utilizing a one-sample test with the historical record as the control (random-historical design) should be employed.

For a significance level of 0.05 and a beta error of 0.3, the average detection time in an area of approximately 1,500 sq mi would be 11 yr for a 20 percent reduction in the number of acres damaged, 2 yr for a 40 percent reduction, and 1 yr for a 60 and 80 percent reduction. If the nonsequential analyses were required, the number of years would be 25, 5, and 1, respectively.

## 1. INTRODUCTION

The evaluation of a cloud seeding experiment to increase precipitation or to decrease hail is a problem of tremendous complexity, because many of the important variables such as pressure, temperature, and wind cannot be controlled. Furthermore, knowledge in atmospheric physics has not advanced enough to permit accurate calculations of the amount of rain or hail that would have fallen naturally on a particular day during a seeding experiment.

The complexity of the evaluation problem has caused controversies and questionable results in both rain enhancement and hail suppression activities. One scientifically oriented project in Colorado did show reduction in hail intensity over a 5-yr period (Schleusener and Auer 1964). Also, a major hail suppression effort in Russia (Sulakvelidze 1966) has apparently been somewhat successful in reducing damaging hail. However, the perplexing problems and the relative infancy of hail suppression activities suggested that preliminary statistical studies concerning type of data collection (Changnon 1969*b*), size of study area, statistical design, and duration of hail suppression experiments should be performed prior to actual experimentation.

This paper presents a statistical methodology utilizing historical hail data for planning and evaluating hail suppression experiments that will give significant results in a minimum amount of time and yet be consistent with valid statistical theory and practical application. A 2.5-yr project designed to study techniques for evaluating potential hail suppression activities in Illinois was conducted by the Illinois State Water Survey during 1966–1968 with primary support from the National Science Foundation (Changnon 1969*a*). One major phase of that project was the study of all available historical hail data in Illinois to develop a desirable methodology.

Only two types of long-term historical hail data were available in Illinois and in most other areas of the United States—the U.S. Weather Bureau point (station) records of hail days, and the crop-hail insurance records of monetary loss and areal extent of damage by counties. A third type of data became available from the operation of a 400-sq mi dense rain-hail measurement network in east-central Illinois during the first year of the project (1967). Individual hailstorm areas (hailstreaks) were carefully delineated from the network data, and although not long-term historical data, these hailstreak data furnished desired information for the evaluation of projects involving individual hailstorms.

A comprehensive report describing all the procedures and nomograms from the Illinois study is available (Schickedanz et al. 1969). It presents the length of experimentation necessary to verify different levels of hail reduction for many different type I and type II error levels, for daily and annual seeding periods, for different sized areas in various locations within the State of Illinois, and for different statistical designs. Procedures and results utilizing the U.S. Weather Bureau hail-day data were reported on earlier by Changnon and Schickedanz (1969), and selected results are given in this paper for comparison.

This paper describes the most salient aspects of the statistical methodology and the more pertinent results derived from the crop-hail insurance and individual hailstreak data. The areas studied ranged from 400 to

4,000 sq mi. These were chosen to match sizes of past hail suppression experiments and those likely to be used in future experiments. Results are presented for the "best" design-test data combinations for an optimum Illinois experiment. These combinations were derived from several statistical tests and designs.

## 2. DATA AND ANALYTICAL PROCEDURES

The number of dollars paid to policy holders for loss of crop yields due to hail, the number of loss days, the number of insured acres damaged by hail, and the area and energy values of individual hailstreaks were investigated as a source of data for the verification of hail modification experiments. The insurance data were considered 1) because of the widespread liability coverage in Illinois and 2) because the most meaningful measure of the success of a hail modification experiment would be its economic benefit. Many researchers have suggested that the paired storm design, for which one member of a given pair of storms is selected at random to be seeded, would allow a more rigorous physical evaluation of the effects due to seeding. Therefore, the individual hailstreak data from a fixed area were considered as a reasonable approximation of the hailfall from individual storms.

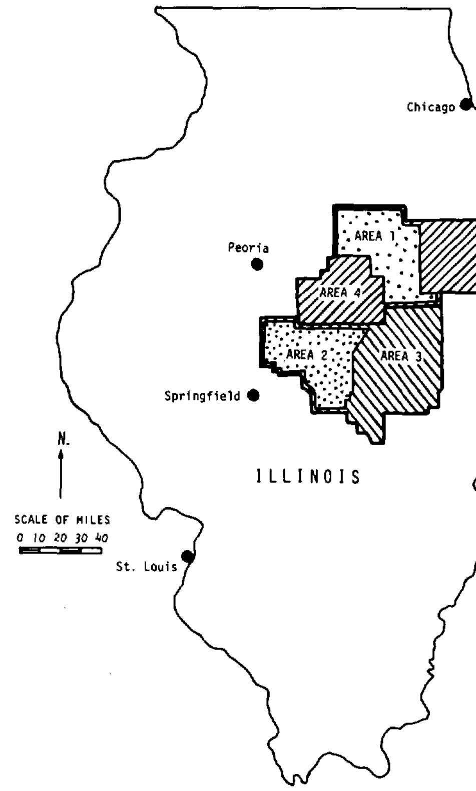


FIGURE 1.—Study areas of crop-hail insurance data.

### CROP-HAIL INSURANCE DATA

Crop-hail insurance data are a very meaningful expression of the effect of hail suppression if they are available for a large portion of an area extensively covered by crops. Importantly, these insurance records show the amount of loss in dollars and the number of acres damaged on a daily and a regional basis. Thus, a potential reduction in hail represents a monetary measurement in the economy of the region. For the present investigation, detailed daily records on individual paid claims for all losses in Illinois during the 1948–1966 period were obtained as unpublished data from the Crop-Hail Insurance Actuarial Association of Chicago. These data and those relating to liability (amount of area insured) were available on a county basis.

The four study areas (fig. 1) were delineated on the basis of county boundaries because of the basic data format, and paired areas of extensive liability and approximately similar size were chosen from the available data. Areas 1 and 2 were 1,531 and 1,598 sq mi, respectively. Areas 3 and 4 were 3,800 and 3,826 sq mi, respectively, and contained the two smaller areas (area 1 is in area 4 and area 2 is in area 3). The average areal coverage of liability (number of square miles with insurance) during the 19-yr period was 80 percent in area 1, 80 percent in area 2, 75 percent in area 3, and 74 percent in area 4.

Although hail insurance data appear to be realistic measures for evaluating hail suppression activities, direct comparison of the loss in 1 mo with that in another, or comparison of the data in 1 yr with that in another, cannot be made without certain adjustments to the data. Adjustments were required for problems of change during a crop season and between years, which include these facts: 1) a given crop's susceptibility to damage fluctuates considerably during the crop season, 2) the amount of liability changes between years, and 3) the value of the dollar changes between years. For valid areal comparisons, another adjustment was required to allow for the fact that the areas were not of the exact same size. Decker (1952) used an adjusted dollar and areal index in a study of hail-damage data in Iowa, and the adjustment indices used in this study are similar. The Illinois indices for seasonal damages in crop susceptibility and temporal changes in liability, as well as the scheme for their employment, are described by Schickedanz et al. (1969). Unless stated otherwise, all loss values presented in this paper are the adjusted values. It should be realized that the indices were developed from the only county yearly data available for adjusting insurance data, and that the adjustments made do not account for all factors of change such as changing farm practices and crop types which are not measured on a county basis.

### NETWORK HAILSTREAK DATA

A dense hail-observing network operated in central Illinois during April–September 1967 furnished detailed data on the surface hail patterns on 26 days of hail (Changnon 1968*a*). The network was located near the center of the four insurance study areas (fig. 1). Areas of hail continuous in time and space, defined as hailstreaks, were delineated within the 400-sq mi study area which

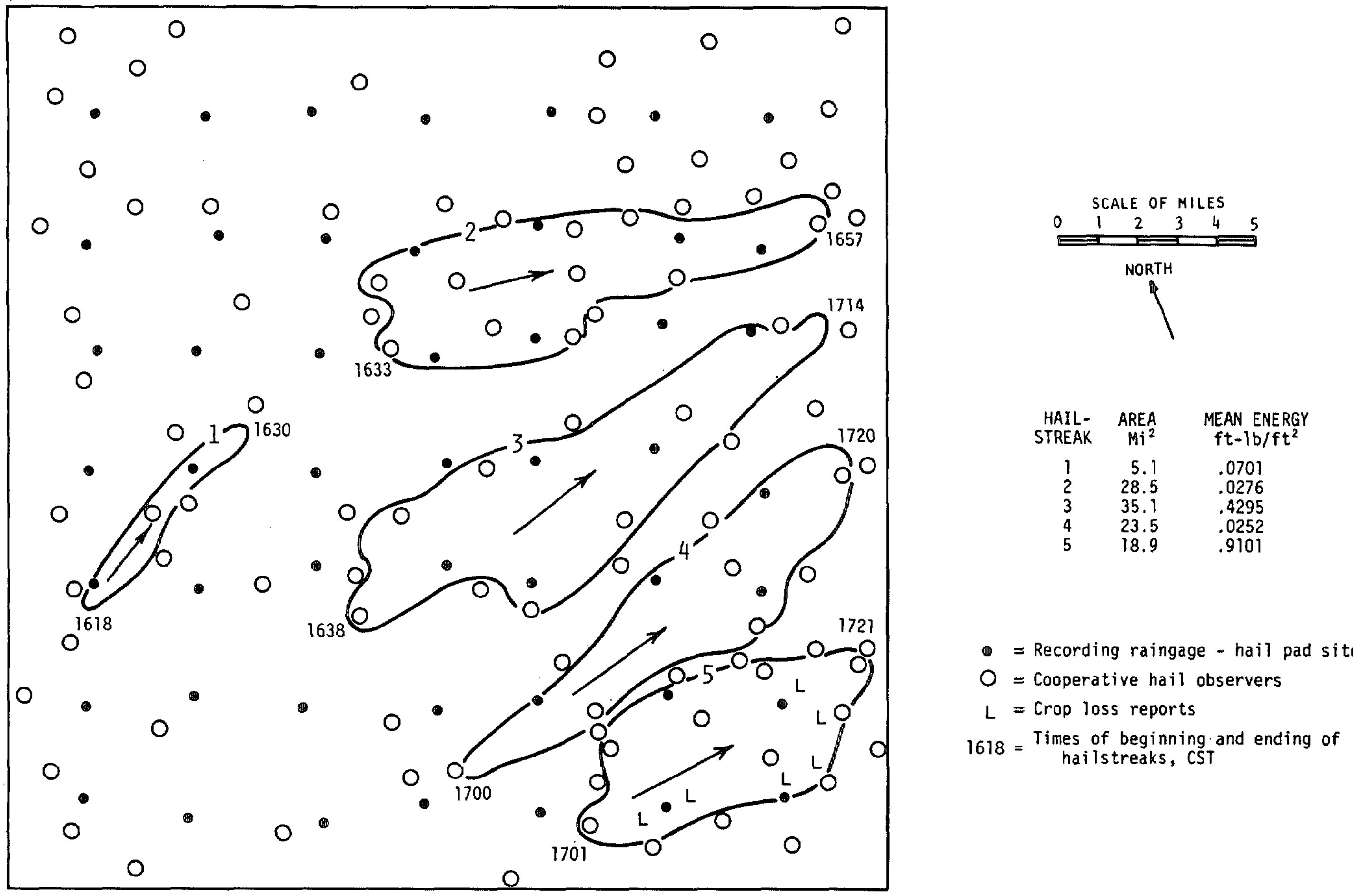


FIGURE 2.—Hail observing points in the study area and complete hailstreaks on June 9, 1967.

contained 98 cooperative hail observers and 49 instrumented sites. Each site had a recording rain gage modified to record time of hail (Changnon 1966) and a 1-sq ft foil-covered hail pad (Wilk 1961) to record hailstone sizes and energy of the hailfalls (fig. 2). The recording rain-gage data allowed the mapping of the individual rain cells, with and without hailstreaks, that crossed the study area during the hailfall periods (Changnon et al. 1967). For those hailstreaks that produced crop damage, unpublished hail insurance data for paid claims also were obtained from the Crop-Hail Insurance Actuarial Association of Chicago. Only those hailstreaks that 1) had at least three locations within the hailstreak boundary with time of hail, 2) had at least two locations with measurable energy values, and 3) occurred entirely within the study area were used in the analysis.

In the 6-mo data collection period, 77 hailstreaks so defined occurred within the area. For each hailstreak, the areal extent was measured, and the area-mean energy imparted by the hailstones was calculated by using the energy values from all hail pads within the hailstreak. An example of the hailstreaks along with their area and energy values, for a hail period on June 9, 1967, is presented in figure 2. There were 13 other hailstreaks in this 1-hr period, but these did not have complete life histories within the study area.

The individual hailstreak study provided expressions of the natural differences between temporally related hailstreaks. These data were then used to determine the required sample size to verify potential suppression experiments that would be based on hailstreak data from a pair of similar clouds where one member of the pair is randomly seeded. In order to more nearly simulate an actual field experiment, certain limiting criteria were defined for selecting hailstreaks for comparison.

First, any two hailstreaks to be compared had to occur within a 1-hr period. This limitation evolved from a basic assumption that any hailstreaks occurring in this area within a 1-hr period likely derived from separate convective clouds that had similar meteorological characteristics prior to their production of hail in the study area. That is, each cloud would have fulfilled any one of several possible criteria of cloud selection, such as moisture content and height, and the two clouds would have developed near enough in time to fit within a realistic operational approach.

Second, all rain cells occurring over the network and not producing hail during the entire period of hail had to be determined and used to represent potentially chosen clouds that did not produce any hail. Third, if a 1-hr period of hailstreaks was separated from another such period by 4 hr or more, the two periods and their hailstreaks were to be considered separate entities for a potential seeding experiment and in our analysis. Hence, two or more discrete 1-hr hail periods could occur in the area on a given day, and 2 days in 1967 did have two such hail periods.

Comparisons were made between the area and energy values of all possible pairs of hail-producing rain cells in a given 1-hr hail period. In the example on figure 2, for which all rain cells had associated hail, the area and energy values of hailstreak number 1 were compared with those of hailstreaks 2, 3, 4, and 5; those of number 2 with 3, 4, and 5; those of number 3 with 4 and 5; and those of number 4 with 5. Thus, there were 10 pairs of hailstreaks for which comparisons were made for the June 9 period. For 77 hailstreaks from 23, 1-hr hail periods in 1967, the above procedure yielded 45 rain cells with no hail, 147 pairs in which both members had hail, 156 pairs in which one member had hail, and 71 pairs in which neither member had hail. The area and energy values of the 77 individual hailstreaks are presented by Schickedanz et al. (1969).

## 3. THEORETICAL FREQUENCY DISTRIBUTIONS

### CROP-HAIL INSURANCE DATA

Theoretical frequency distributions were fitted to the insurance and hailstreak data so that subsequent statistical analysis could be performed. The great temporal variability of the yearly acres of damage values for areas 3 and 4 are illustrated in figure 3. The annual insurance data were tested for randomness in the climatological data series using the procedure of Swed and Eisenhart (1943). The probabilities of obtaining a test statistic different from that expected by random sampling were greater than 0.10 for the insurance data in all four areas. On the basis of this test, the yearly insurance data were treated as homogeneous data series for the subsequent statistical analysis.

The gamma and log-normal distributions were then fitted to the yearly loss data, and the Kolmogorov-Smirnov goodness-of-fit test was applied. Since both parameters of each distribution are estimated from experimental data, the more common tables of $D_n$ were not used, nor are they valid. Used instead were new tables of $D_n$ computed by Liffiefors (1967) which take this factor into consideration. The goodness-of-fit test showed that the gamma distribution provided a better fit than the log-normal distribution for the yearly data. The probabilities of obtaining a larger test statistic from random sampling were all greater than 0.05 for the gamma distribution except for dollar loss in area 2 for which the probability was 0.046.

In the initial analysis of the daily data, the days with crop-hail damage were separated from the many days without crop-hail damage. A mixed distribution function

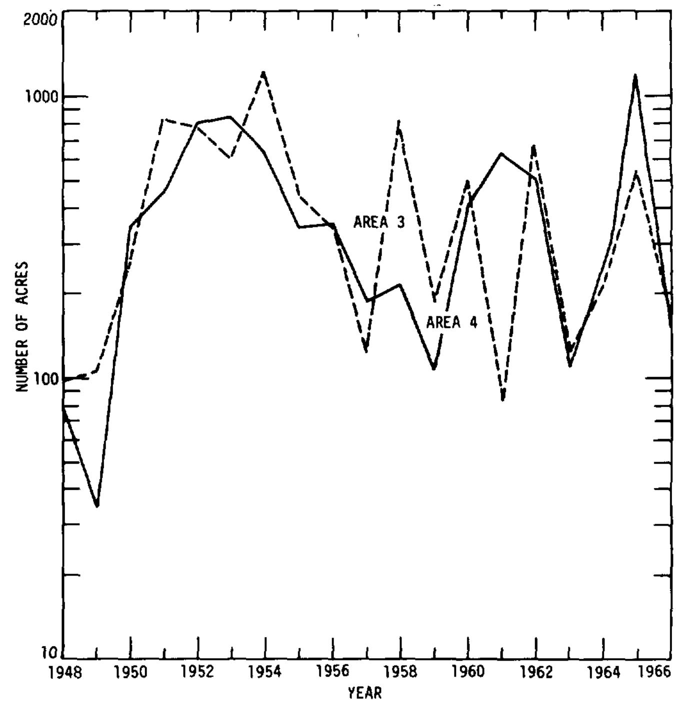


FIGURE 3.—Annual amount of acre loss in areas 3 and 4.

was then estimated on the basis of two assumptions. First, there is a nonzero probability of hail on a particular day. Second, when damage does occur, the amount of damage is distributed as a log-normal or gamma variable. The general form of the mixed distribution function $[G(x)]$ can be written as

$$G(x)=P(X<a)=P(X=0)+P(X>0)\cdot P(X<a|X>0) \quad (1)$$

where

$P(X<a)$ = probability of receiving less than a specified amount of hail damage,

$P(X=0)$ = probability of receiving no hail damage,

$P(X>0)$ = probability of receiving some hail damage, and

$P(X<a|X>0)$ = probability of receiving less than a specified amount of hail damage, given that hail damage has occurred.

The term $P(X<a|X>0)$ is given by

$$P(X<a|X>0)=F(x)=\int_0^a f(x)dx. \quad (2)$$

The density function, $f(x)$, can be specified as any distribution.

The chi-square goodness-of-fit test was then applied to the nonzero portions of the mixed distribution functions for the assumptions of gamma and log-normal distributions. The chi-square test was based on the method described by Hahn and Shapiro (1967) with one modification: the number of class intervals was chosen on the basis of the relation $5 \log_{10} N$, where $N$ is the number in the sample. This method insures that the choice of class interval boundaries will depend on the theoretical values and not on the sample values. It also insures that, except for modification of class interval limits due to rounding and measurement errors, equal numbers of expected values will result in each interval. The above rule also insures that there will be at least five expected values in each interval as long as the sample is 40 or more. This chi-square procedure makes comparisons between different distributional fits more objective.

It was found that none of the daily insurance data could be fitted by the gamma distribution. The data also were poorly fitted by the log-normal distribution for the area 3 monetary data and for acreage data in areas 3 and 4. The dollar data for area 2 were close to the 0.05 significance level, and the rest of the data could be fitted by the log-normal distribution. With the exception of areal comparisons, the computation of sample size was based on data from area 1, and the log-normal distribution consequently was used for the subsequent statistical tests. Later work has indicated that the data in areas 3 and 4 can be fitted by a truncated log-normal distribution.

The Poisson and negative binomial distributions were then fitted to the number of days on which hail damage occurred in the four areas. These distributions were fitted to hail damage days in the categories of greater than \$50 loss, \$100 loss, \$150 loss, \$200 loss, and total loss. Application of the Kolmogorov-Smirnov test for the 20 resulting distributions showed that 10 of the cases were inadequately described by the Poisson distribution. For these 10 cases, the test of sufficiency indicated that the moment estimates of the negative binomial were not sufficient. However, for the daily loss categories of $\geq$\$150 loss and $\geq$\$200 loss, all data could be fitted by the Poisson distribution or by the moment estimates of the negative binomial distribution, even though the moment estimates were insufficient for the $\geq$\$150 loss category in areas 2 and 3. As more of the low daily loss values were excluded from the distribution, the better the fit became in all areas. Since the low loss days did not fit the distributions well, only the data for the hail days producing $\geq$\$150 loss and $\geq$\$200 loss were selected for further analysis.

### NETWORK HAILSTREAK DATA

When the log-normal distribution was fitted to the hailstreak data, differences between the area and energy data were readily demonstrated. The area data were nicely fitted by the nontruncated log-normal distribution, but the energy data required a truncated log-normal distribution with a truncation point of 0.00215. The truncated distribution was obtained by deleting from the sample all values$\leq$0.00215 ft-lb/sq ft, and by making the transformation $(x-0.00215)$ on the remainder of the sample. The log-normal mean and variance were then estimated from the transformed sample. The fact that only 47 values were left out of a sample of 77 illustrates the severity of the truncation. Hailstreak area values ranged from 0.9 to 40.3 sq mi (average was 9.7 sq mi), and the mean energy values ranged from 0.0001 to 12.6559 ft-lb/sq ft (average was 0.2575).

In the paired storm design for a hail suppression experiment, a pair of clouds with similar characteristics is selected, and one member of the pair is then chosen at random to be seeded. The 147 pairs of rain cells in which both members had associated hailstreaks were assumed to have originated from separate clouds with similar characteristics. Thus, the associated hailstreaks were assumed to be hail that would have been produced from clouds meeting the paired storm design criteria. After one member of each pair was selected at random as seeded, the differences between the areas and between the energy values of the seeded and nonseeded hailstreaks were then computed, and the cumulative ogives for the empirical distributions of differences were formed. These distributions were designated as the natural distributions, that is, the distributions expected if seeding had not occurred. The values of the seeded hailstreaks were then reduced 20, 40, 60, and 80 percent, and the respective cumulative ogives were formed (fig. 4). The differences in the curves are assumed to be the effect that seeding would have on the natural distributions.

A mixed distribution was then estimated on the basis of two assumptions. First, there is a nonzero probability of obtaining a pair of rain cells which have associated hail with each member. Second, when such a pair occurs, the differences of area (or of energy) are distributed in the form of the cumulative distributions of figure 4. The general form of the mixed distribution function is the same as equation (1), except the terms are defined as follows:

$P(X<a)$ = probability of receiving less than a specified difference of area (energy),

$P(X=0)$ = probability of having experienced a pair of rain cells with only one member having associated hail, or neither member having associated hail,

$P(X>0)$ = probability of having experienced a pair of rain cells with both members having associated hail, and

$P(X<a|X>0)$ = probability of receiving less than a specified difference of area (energy) given that a pair of rain cells which has both members seeded has occurred.

The term $P(X<a|X>0)$ is given by equation (2) where the density function, $f(x)$, is specified to be the derivative of the cumulative ogives from figure 4.

## 4. EXPERIMENTAL DESIGNS AND TESTS OF HYPOTHESES

Sample size was computed for six designs using the crop-insurance and the hailstreak data. These designs

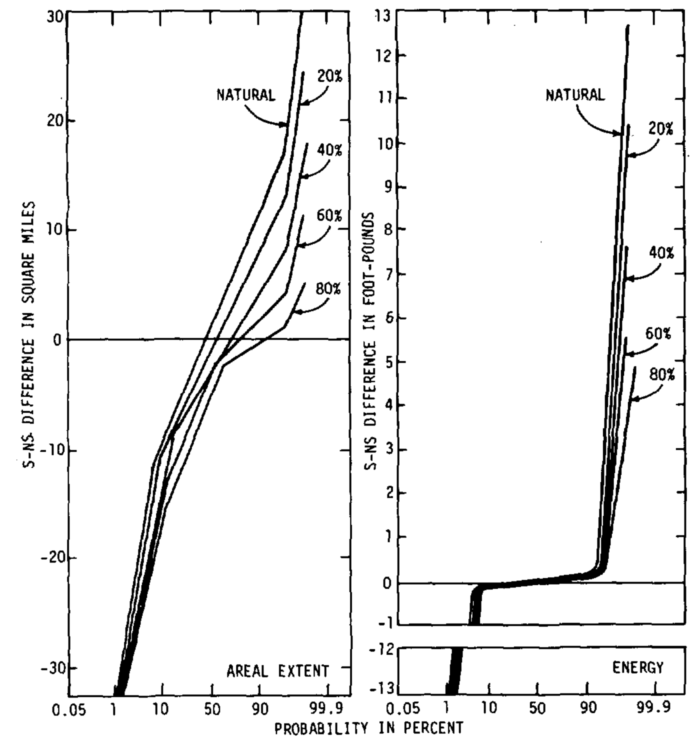


FIGURE 4.—Empirical distributions of areal extent and energy of hailfall.

included 1) randomization of days over a single target area into seeded and nonseeded days with the nonseeded days being the control (single area-random), 2) random choice of days to be seeded over a single target area with the historical record being the control (random-historical), 3) continuous seeding (on all potential hail days) with the historical record being the control (continuous-historical), 4) seeding in a target area chosen at random with another area being the control (crossover), 5) continuous seeding (all potential hail days) in a target area with a nearby area being the control (target-control), and 6) seeding one member of a given pair of storms at random (paired storm).

## CROP-HAIL INSURANCE DATA

Initially, the yearly insurance data were considered as the experimental unit in the various designs. A yearly unit does not appear as practical as the daily unit since the yearly sample size is much smaller and much of the areal-temporal variability is masked by other factors. Nevertheless, sample size was computed for the various designs and tests using yearly data to check its potential applicability.

The normal sample test was used with all of the experimental designs. Under the assumption that the yearly data were log-normal distributed, various reductions of $\delta=0.05$, 0.10, 0.20, 0.40, 0.60, and 0.80 were assumed and applied to the nontransformed hail data. The corresponding change on the transformed scale was made by adding the logarithm of $(1-\delta)$. The variances were assumed to be equal since the variance of the log-normal distribution is unaffected by scale changes in the variate. Relationships given by Schickedanz et al. (1969) were used to determine the size of sample necessary to obtain significance for various reductions and various levels of type I and type II error. For yearly data, these sample sizes were computed for one- and two-sample normal tests; with both the sequential (Thom 1957) and nonsequential analysis; and for the single area-random, random-historical, continuous-historical, target-control, and crossover designs.

The gamma test was also used with the yearly data. Under the assumption that the slope factor is constant, various reductions were applied to the scale parameter. Sample sizes were then computed for the one- and two-sample gamma tests involving the sequential and nonsequential analysis (Thom 1957, Schickedanz et al. 1969, Schickedanz 1967).

The procedures used in evaluating the yearly data were also applied to the daily data. In addition, the Poisson and negative binomial one-sample tests were applied to distributions of the number of damage days for the random-historical and continuous-historical designs. The methods were the same as those used in a study of U.S. Weather Bureau hail-days (Changnon and Schickedanz 1969). The seeding effect was first simulated by superimposing a scale decrease on the areal parameters of the nonseeded distributions. The number of years required to obtain significance was then determined through algebraic relations. The duration of a seeding experiment based on daily data was obtained by the same equations that were used to estimate sample size for the crop insurance yearly data and the U.S. Weather Bureau hail-day data.

## NETWORK HAILSTREAK DATA

Because of the dependence between members of pairs, the appropriate test to use for the hailstreak data is the Wilcoxin Matched Pair Signed Rank test. The number of years required to obtain significance for assumed decreases of 20, 40, 60, and 80 percent was derived by generating sample values from the curves of figure 4. As each sample value was generated, a tabulation was made of whether significance was obtained for the Wilcoxin Matched Pair Signed Rank test. This was continued until a specified number of values had been generated. The process was then repeated, so that a frequency distribution of the number of runs significant at a particular sample size was obtained. The percentage number of significant runs at each sample size is equivalent to the power of the test.

This method assumes that one would be able to forecast which clouds would produce hail (the hailers). If the clouds chosen for a particular pair were both "nonhailers," the time required would be increased since tied values are dropped from the Wilcoxin test. If one member of the pair is a hailer and one is a nonhailer, the differences between the two would tend to be smaller which in turn would increase the amount of time required. For the 1-yr sample of storms used, 42 percent of all possible combinations of pairs had only one nonhailer, and 19 percent were pairs in which both members were nonhailers.

## 5. RESULTS

Results are presented herein for the insurance and hailstreak data. In addition, considerable research on the hail-day data from U.S. Weather Bureau stations in five State areas has been performed to study their use in the evaluation of hail suppression experiments (Changnon and Schickedanz 1969). Certain results from the hail-day study have been included in this section for comparison with those from the insurance and hailstreak data.

### NUMERICAL RESULTS

Comparison of results for various designs (table 1) reveal that a continuous seeding design utilizing the historical record would require the least amount of time to detect a 20 percent decrease in hail (11 yr). The random seeding design in which the historical information is not used requires the most time. In fact, unless one can produce 60 percent reductions in hail, this design is virtually useless (116 yr for 20 percent decrease versus 7 yr for 60 percent decrease for $\beta=0.2$). The target-control and crossover designs, because of the poor correlation of hail loss between areas (+0.2 or less), is a very undesirable design for hail suppression experiments. Since the validity for a completely continuous design is somewhat questionable, the random-historical and the paired storm designs remain as the most reasonable choice of designs for a hail suppression experiment. The paired storm design has a smaller sample size than the random-historical design. However, this estimate of sample size does not include the effect of the nonhailers as one or both members of the pair. In all probability this effect would be to inflate the sample size estimates for the paired storm design in table 1. If one allows a one-fifth randomization factor, the random-historical design takes on even more favorable properties.

Comparison of results for various types of data (table 2) reveal that, for $\beta=0.2$, U.S. Weather Bureau annual hail-day data required the least amount of time to detect a 20 percent decrease (11 yr) followed by the daily insurance acreage data (13 yr). The yearly insurance dollar data required the most time to obtain significance, 59 yr. The energy data are not complete for the smaller decreases for these values of $\beta$, but indications are that at the smaller decreases the time required is similar to yearly insurance data (Schickedanz et al. 1969). Certainly, much more time is required for hailstreak energy data than for hailstreak areal extent data. Since insurance loss data are considered the most meaningful hail expression and since hail-day frequency data do not relate well to loss data (only 42 percent of the variation in dollar loss due to hail damage can be attributed to hail days), it appears that the insurance data may be a better parameter to detect seeding effects, even though it requires slightly more time than the hail-day data.

TABLE 1.—*Years required to detect 10, 20, and 60 percent decreases according to design for the "best" test-analysis type of data combination ($\alpha=0.05$)*

| | | Number of years required | | |
|---|---|---|---|---|
| | $\beta$ | 10% | 20% | 60% |
| Continuous seeding with historical record being the control (continuous-historical)—U.S. Weather Bureau hail-day data | 0.2 | 46 | 11 | 1− |
| | 0.5 | 17 | 4 | 1− |
| Random seeding of one member of a pair of storms with nonseeded member being the control (paired storm)—network data | 0.2 | * | 16 | 1− |
| | 0.5 | * | 9 | 1− |
| Random seeding with unseeded events being the control, one-half randomization (random-historical)—U.S. Weather Bureau hail-day data | 0.2 | 92 | 22 | 2 |
| | 0.5 | 34 | 8 | 1− |
| Continuous seeding with random choice of areas and nonseeded area being the control (crossover)—crop-hail insurance data | 0.2 | 202 | 45 | 3 |
| | 0.5 | 88 | 20 | 1− |
| Continuous seeding with fixed target and control areas (target-control)—crop-hail insurance data | 0.2 | 493 | 110 | 6 |
| | 0.5 | 216 | 48 | 2 |
| Random seeding with unseeded events being the control (single area-random)—crop-hail insurance data | 0.2 | 518 | 116 | 7 |
| | 0.5 | 226 | 51 | 2 |

*Results not available

Manmade decreases in summer and annual hail-day frequencies in areas 3 and 4 would require less time to detect than comparable ones in the other areas (table 3), and changes in area 2 would require considerably more time than in the other areas. The lowest values in table 3 are for the largest areas which have the largest average number of hail days, and this suggests that the higher the average hail days, the lower the time required to obtain significance. Area 2 requires the most time because of nonrandomness in the climatological data series (Schickedanz et al. 1969).

In general, as the number of damage days increases and the size of area increases, the sample size required to obtain significance is decreased in the daily insurance data (table 3). The trend is much less in the yearly data, almost nonexistent.

In table 4 there is a comparison between the sequential and nonsequential analysis for the daily insurance data. On the average, the sequential analysis reduced the number of required observations by approximately 58 percent for a type II error of 0.2 and 63 percent for a type II error of 0.5. For summer hail-day data, the average reduction was 60 percent for a type II error of 0.5 when all areas were considered (Changnon and Schickedanz 1969).

### DISCUSSION OF OPTIMUM DATA, DESIGNS, AND TESTS

Even though there are problems inherent in the insurance data (changing liability and seasonal variability in crop susceptibility), these daily data afford the most meaningful measure of detecting seeding effects from a hail suppression program. In this regard the insurance acre-damaged data required less time than monetary loss data to obtain significance.

The choice of insurance crop-loss data as the basic hail measurement to realize the goal of an optimum Illinois experiment also brings with it certain restrictions on other design factors (Changnon 1969*a*). First, the shortest

TABLE 2.—*Years required to detect 10, 20, and 60 percent decreases according to type of data for "best" design-test-analysis combination* ($\alpha=0.05$)

| | $\beta$ | Number of years required 10% | 20% | 60% |
|---|---|---|---|---|
| U.S. Weather Bureau annual hail days (area 5) | 0.2 | 46 | 11 | 1 |
| | 0.5 | 17 | 4 | 1− |
| Insurance acres-damaged data, daily (area 1) | 0.2 | 56 | 13 | 1− |
| | 0.5 | 21 | 5 | 1− |
| Insurance dollar-loss data, daily (area 1) | 0.2 | 69 | 15 | 1− |
| | 0.5 | 26 | 6 | 1− |
| Hailstreak data, areal extent (network) | 0.2 | * | 16 | 1− |
| | 0.5 | * | 9 | 1− |
| Hail during days ≥$150 loss (area 1) | 0.2 | 130 | 31 | 3 |
| | 0.5 | 48 | 12 | 1 |
| U.S. Weather Bureau summer hail days (area 5) | 0.2 | 162 | 39 | 4 |
| | 0.5 | 60 | 14 | 1+ |
| Insurance acres-damaged data, yearly (area 1) | 0.2 | 178 | 41 | 3 |
| | 0.5 | 66 | 15 | 1+ |
| Insurance dollar-loss data, yearly (area 1) | 0.2 | 255 | 59 | 4 |
| | 0.5 | 94 | 22 | 2 |
| Hailstreak data, energy (network) | 0.2 | * | * | 3 |
| | 0.5 | * | * | 1+ |

*Results not available

TABLE 3.—*Years required to detect 20 percent decrease according to area for the continuous design and sequential analysis* ($\alpha=0.05$ and $\beta=0.20$)

| Area | Average number of days | Area size (mi²) | Number of years required to detect 20% reduction |
|---|---|---|---|
| U.S. Weather Bureau annual hail days | | | |
| 1 | 7.7 | 1000 | 8.1 |
| 2 | 8.3 | 1000 | 26.7 |
| 3 | 9.1 | 1000 | 6.9 |
| 4 | 11.0 | 3000 | 5.7 |
| 5 | 5.7 | 500 | 11.1 |
| Average | | | 11.7 |
| U.S Weather Bureau summer hail days | | | |
| 1 | 2.5 | 1000 | 39.2 |
| 2 | 2.4 | 1000 | 78.2 |
| 3 | 2.2 | 1000 | 28.7 |
| 4 | 3.4 | 3000 | 27.8 |
| 5 | 1.6 | 500 | 39.0 |
| Average | | | 42.6 |
| Insurance data, yearly acres | | | |
| 1 | 16.6 | 1000 | 41.3 |
| 2 | 21.0 | 1000 | 32.7 |
| 3 | 27.9 | 4000 | 34.9 |
| 4 | 32.2 | 4000 | 35.4 |
| Average | | | 36.1 |
| Insurance data, daily acres | | | |
| 1 | 16.6 | 1000 | 12.6 |
| 2 | 21.0 | 1000 | 9.8 |
| 3 | 27.9 | 4000 | 7.7 |
| 4 | 32.2 | 4000 | 6.7 |
| Average | | | 9.2 |

time period of data separation is 1 day since only the day and not the time of loss is known. Hence, designs based on seeding of individual storms cannot be employed with these data. Second, in order to be valid these data should come from areas with 60 percent or more insurance coverage (Changnon 1968*b*). This necessity limits experimentation to such areas and restricts the period of experimentation to May 1 through October 15, the crop season.

TABLE 4.—*Comparison of the number of years required to detect 10, 20, and 60 percent decreases for the "best" design-test combination for daily insurance data* ($\alpha=0.05$)

| | $\beta$ | Number of years required for percentage reductions 10% | 20% | 60% |
|---|---|---|---|---|
| | | Acres | | |
| Sequential | 0.2 | 56 | 13 | 1- |
| | 0.5 | 21 | 5 | 1- |
| Nonsequential | 0.2 | 129 | 29 | 2 |
| | 0.5 | 57 | 13 | 1- |
| | | Dollars | | |
| Sequential | 0.2 | 69 | 15 | 1- |
| | 0.5 | 26 | 6 | 1- |
| Nonsequential | 0.2 | 159 | 40 | 2 |
| | 0.5 | 69 | 17 | 1- |

A means of choosing which design and test to use is illustrated schematically in figure 5, in which all tests and designs employed in this research are represented. Zone A contains the family of designs and tests that yield the least amount of time to obtain significance, although some of the statistical assumptions and techniques may be questionable. Zone C incorporates the designs and tests with the most stringent requirements on randomization and assumptions (hence, most valid), but its designs require the longest time to obtain significance. Since the designs and tests in zone C require exorbitant sample sizes and those in zone A are not always valid, the family of designs and tests in zone B are the most logical to use. The B zone would include the one-sample tests with both the sequential and nonsequential analytical approach and some randomization in the design.

Accordingly, the recommendation resulting from this hail suppression research is to use the single area design in which all potential storms on a particular day are seeded with the randomization being applied to days rather than storms. The randomization factor could vary from one-half to one-fifth, the smaller fractions being preferable. That is, 50 to 20 percent of the days should not be seeded, but should be retained for a control in the experiment. This selection of days would best be done randomly. Another possibility, since 21 percent of Illinois hail occurs at night, would be to designate the days with nocturnal storms to be the nonseeded days. Such designation would eliminate night seeding which is difficult with present techniques, but might introduce bias into the evaluation. If the climatological data series are random over time, the sequential approach is the best one to use in verifying the results. The risks involved in the sequential analysis, as opposed to the nonsequential

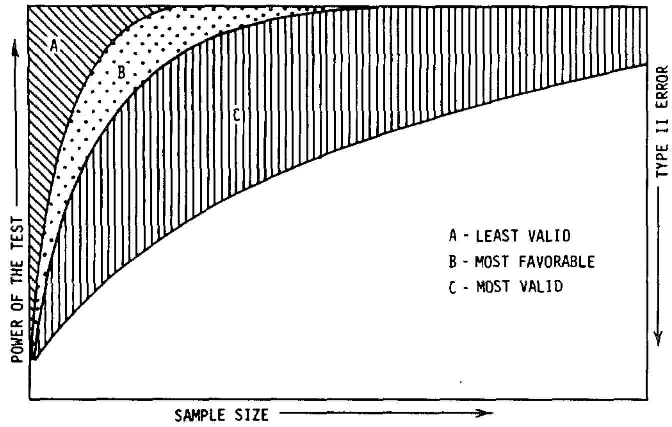


FIGURE 5.—Schematic representation of validity zones for various tests and designs.

approach, are outweighed by the smaller sample sizes required in the sequential analysis. Preference for the sequential analysis is supported by the practical fact that hail observations and field operations are expensive, difficult, and time consuming.

A choice of geographical site was made by Changnon (1969*a*) on the basis of results which showed 1) where reductions could be detected fastest and 2) where heavily insured areas existed. The preferred sites of an experiment in Illinois would be either in the western portion or in the east-central portion.

The size of the experimental area for an optimum experiment with insurance area-of-loss data would be between 3,000 and 4,000 sq mi. However, if potential experiments are based on other forms of surface hail data, the size of the smallest area that could furnish meaningful hail measures will be critical because of the high costs of surface instruments and data collection. Analysis of the sizes and motions of hailstreaks suggested that the minimum size of a study area could be 300 sq mi (Changnon 1969*a*).

Any 1-yr experiment in hail suppression will involve risks in deriving meaningful conclusions, regardless of how sophisticated the statistical analysis may be. For this length of experiment, a 40 percent decrease is the minimum decrease which can be detected with a significance level of 0.05 and type II error of 0.5 (that is, the probability of rejecting a seeding-produced decrease in hail when the decrease actually existed). Detection of smaller decreases for a 1-yr experiment is accompanied by a rapid increase in the type II error.

For a significance level of 0.05 and a power (that is, the probability of detecting a seeding decrease when seeding decrease is present) of 0.50, the minimum number of years required to detect a 20 percent decrease with a continuous seeding design is 4 yr for U.S. Weather Bureau hail days and 5 yr for daily insurance data. For a power of 0.80, the values are 11 and 13 yr, respectively. When the optimum size of area is used for the insurance data, the figure of 5 reduces to 3 yr (Schickedanz et al. 1969). With randomization in the experiment, this value increases, as it does also with the classical nonsequential analysis.

The expected number of years of the experiment will then vary from 1 to 5 yr if the reduction in amount of loss area is somewhere between 80 and 20 percent, and a type II error of 0.50 is required. The years would vary from 1 to 13 for a type II error of 0.20. If a 10 percent or lower reduction is produced, experimentation would have to extend for at least 21 yr before a definitive measure could be established. Various hail suppression projects in Russia, Canada, and Kenya have claimed reductions in the 40 to 70 percent range. These successes have been largely with mountain-bred hailstorms, and such reductions may or may not be possible with the largely frontal type hailstorms of Illinois. However, if reductions of these magnitudes can be produced in Illinois, the experiment would need to persist for only 3 yr or less.

## RECOMMENDED EVALUATION PROCEDURE

The recommended evaluation procedure for a seeding experiment is to first select an area in which the historical data series are random over time. This condition then makes it possible to employ the sequential analytical approach for the acre-loss data if appropriate distribution functions can be fitted to the data.

The optimum experimental plan is to seed 80 percent (randomly chosen) of the forecasted hail days. The cumulative area of loss, as based on the total damaged area on the seeded days of each year, is plotted against the number of years from the start of the experiment. When the cumulative total falls outside the "band" formed by the rejection and acceptance lines (as determined from the sequential theory and the historical distribution of hail loss from the study area), the experiment is terminated. If the cumulative value falls below the band, suppression has been achieved (accepted), but if the cumulative value falls above the band, the seeding has had no suppressive effect (rejected). Once the cumulative total indicates successful suppression, the percent reduction achieved is computed as the difference between the mean (for area of loss) calculated from the historical (unseeded) record and the mean calculated from the seeded sample period.

In addition, the data from the nonseeded days would be used to check for trends in the data from the experimental period. If a trend is evident, the experiment should be continued for the number of years specified for a one-sample test, but with the nonsequential analytical approach (Schickedanz et al. 1969). A one-sample test would then be made with the historical record as the control.

For such an important and expensive experiment, the beta error (the risk of not detecting the seeding effect if it exists) should not be greater than 0.3 and the significance level should be 0.05. Under these conditions, the average detection would be 11 yr for a 20 percent reduction in number of acres damaged, 2 yr for a 40 percent reduction, and 1 yr for a 60 and 80 percent reduction, using the sequential analysis in an area of approximately 1,500 sq mi. If the nonsequential analysis was required, the years for detection of these reductions would be 25, 5, and 1, respectively.

## 6. CONCLUSIONS

This research has provided information on the type of hail data, the experimental design, geographical site, areal extent, duration, and evaluation techniques for a hail suppression experiment in Illinois. The methodology presented is applicable to other climatic areas provided the appropriate historical record and theoretical distribution functions are used, although the Illinois nomograms may be only first approximations of those for other hail climates.

The optimum design is the random-historical design with one-fifth of the days being retained for a control. The optimum hail measurement is insurance acres-damaged data, and the optimum experimental unit is the day. The optimum analytical procedure for hail data is the sequential analytical approach.

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